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恒热流竖壁降膜发展段流动换热分析

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[摘要]　采用边界层相似解对恒热流竖壁下降液膜发展段中的层流流动与换热特性进行了分析,获得了发展段长度,液膜厚度和无量纲换热系数的计算表达式。

关键词　降膜　发展段　速度边界层　温度边界层
中图分类法　TK 124

0　前言

降膜换热在能源,动力,化工,制冷,核反应堆等工业领域有着广泛的应用。对降膜换热的研究多侧重于液膜发展段,对液膜发展段中的流动,一些研究人员通过理论分析,数值计算和实验研究作了许多探索工作,Yih, S. M对此作过综述[1]。然而,液膜发展段中的流动机理仍不十分清楚,而对液膜发展段中的换热特性,研究得就更少了。本文应用边界层相似性解,研究了恒热流竖壁降膜层流发展段中的流动和换热特性,得到了发展段长度,液膜厚度和换热系数的计算式。

1　模型和控制方程

液膜流动的布液方式多种多样,从而使得液膜发展段中的流动也互不相同。本文考虑的物理模型及所选择的坐标系如图 1所示。液体通过一个竖直壁面和一个水平壁面之间的窄缝,在竖壁上形成液膜稳定均匀地向下流动。液体温度与水平壁温度都为 T_0,竖壁向液膜传递恒定热流 q_w,液膜自与竖壁接触即开始形成速度边界层与温度边界层,随着向下流动,边界层厚度增大,直到在下游某处,边界层厚度等于整个液膜的厚度。为简化分析作如下假定:

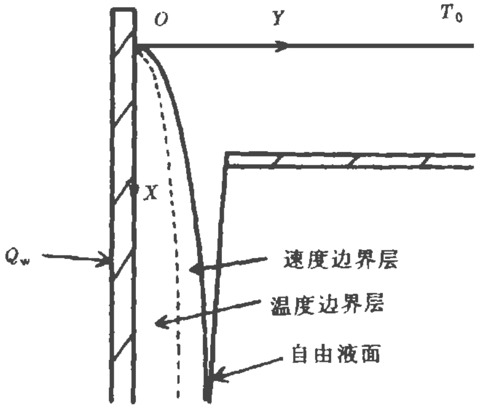

图 1　边界层发展段流动

(1)壁面在垂直于 xoy平面的方向上为无限大,因此,xoy平面上的流动为二维问题。

(2) 流体为常物性牛顿流体。

(3) 流动是定常不可压缩层流流动。

(4) 竖壁与水平壁之间的窄缝的宽度足够大,流动不属于小孔出流问题,因而在

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液膜流出窄缝之前和之后,边界层都稳定连续地发展。

(5) 液膜内的压力变化及自由表面的波动忽略不计。

这样,在竖壁面上将产生一个作粘性流动的速度边界层,而在此边界层外边,则是重力作用下的势流,其速度以 u_p 表示为

$$u_p = \sqrt{2gx} \tag{1}$$

且有

$$g = u_p \frac{\mathrm{d}u_p}{\mathrm{d}x} \tag{2}$$

式中 g 为重力加速度。按照相似理论[2],引入相似变量 Z,对边界层动量与能量方程进行变换,可得

$$f''' + ff'' - \frac{2}{3}f'^2 + \frac{2}{3} = 0 \tag{3}$$

$$\theta'' + Prf\theta' - \frac{1}{3}Prf'\theta = 0 \tag{4}$$

$$Z = 0,\quad f = 0,\quad f' = 0,\quad \theta = 1 \tag{5}$$

$$Z \to \infty,\quad f' \to 1,\quad \theta \to 0 \tag{6}$$

式中 f 和 θ 分别为无量纲流函数和无量纲温度,Pr 为流体的普朗特数,用龙格—库塔迭代法求解该方程组,得到问题的数值解,表 1和表 2分别列出了动量方程和能量方程的部分计算结果。

表 1　动量方程计算结果

Z	0.0	1.0	2.0	2.5	2.6	2.7	3.0
f	0.0000	0.4113	1.2774	1.7645	1.8633	1.9624	2.2609
f'	0.0000	0.7203	0.9564	0.9868	0.9894	0.9922	0.9967

表 2　能量方程计算结果

pr	2	3	4	5	6	7
$\theta'_{\eta=0}$	0.878	1.013	1.118	1.207	1.284	1.352

2　流动与换热分析

2.1　流动

由流函数定义式[2]可得边界层内速度分布

$$u = u_p f'(Z) = \sqrt{2gx}\, f'(Z) \tag{7}$$

$u/u_p = f'(Z) = 0.99$ 处的 y 值即为边界层厚度,以 W表示,由相似变量定义得

$$y = Z\left[\frac{4\mathrm{g}}{3\sqrt{2g}}\right]^{\frac{1}{2}} x^{\frac{1}{4}} \tag{8}$$

由表 1可知,使 $f' = 0.99$ 的 Z在 2.6与 2.7之间,作为近似分析,按线性插值,取此值为 2.6214,可得

$$W = 3.027\left[\mathrm{g}/(2g)^{\frac{1}{2}}\right]^{\frac{1}{2}} x^{\frac{1}{4}} \tag{9}$$

设速度边界层内流量为 Q_1,以 d表示液体密度,则

$$\begin{aligned} Q_1 &= \mathrm{d}\int_0^W u\,dy \\ &= \frac{2}{3}\mathrm{d}\left[\mathrm{g}(2g)^{\frac{1}{2}}\right]^{\frac{1}{2}} x^{\frac{3}{4}} \int_0^W f'(Z)\,dZ \\ &= 2.1744\mathrm{d}(\sqrt{2g}\,\mathrm{g})^{\frac{1}{2}} x^{\frac{3}{4}} \end{aligned} \tag{10}$$

又设边界层外液膜厚度为 U,流量为 Q_2,有

$$Q_2 = \mathrm{d}\sqrt{2gx}\,\mathrm{U} \tag{11}$$

若总流量为一定值 Γ,则

$$\begin{aligned} \Gamma &= Q_1 + Q_2 \\ &= 2.1744\mathrm{d}(\sqrt{2g}\,\mathrm{g})^{\frac{1}{2}} x^{\frac{3}{4}} + \sqrt{2g}\,\mathrm{dU}x^{\frac{1}{2}} \end{aligned} \tag{12}$$

由此得

$$\mathrm{U} = \left[\Gamma - 2.1744\mathrm{d}(\sqrt{2g}\,\mathrm{g})^{\frac{1}{2}} x^{\frac{3}{4}}\right]/\mathrm{d}\sqrt{2g}\,x^{\frac{1}{2}} \tag{13}$$

将一定流量下,降膜发展段液膜总厚度为 h 表示,则有 $h = \mathrm{W} + \mathrm{U} = 3.027(\mathrm{g}/\sqrt{2g})^{\frac{1}{2}} x^{\frac{3}{4}} + \left[\Gamma - 2.1744\mathrm{d}(\mathrm{g}\sqrt{2g})^{\frac{1}{2}} x^{\frac{3}{4}})\right]/\mathrm{d}\sqrt{2g}\,x^{\frac{1}{2}}$　(14)

速度边界层发展到整个液膜厚度时,$Q_2 = 0$,$Q_1 = \Gamma$,此时流动区域的长度即为流动发展段长度 x_{en}。由

$$\Gamma = 2.1744\mathrm{d}(\mathrm{g}\sqrt{2g})^{\frac{1}{2}} x_{en}^{\frac{3}{4}} \text{得}$$
$$x_{en}(g/\mathrm{g}^2)^{\frac{1}{3}} = 0.0444Re^{\frac{4}{3}} \tag{15}$$

式中 $Re = 4\Gamma/\_$,_ 为液体动力粘度,x_{en} 与 Re 的关系示于图 2。

2.2　换热

温度边界层换热系数以 T表示

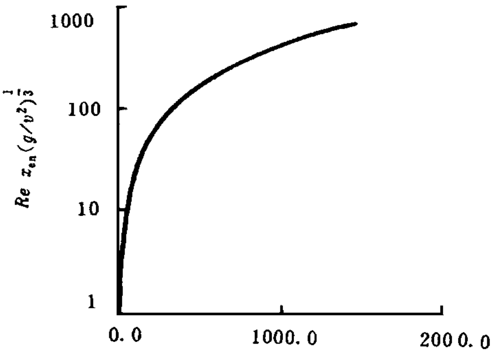

图 2　x_{en} － Re的关系 曲线

$$\mathrm{T}=\frac{\lambda\frac{\partial T}{\partial y}\Big|_{y=0}}{T_W-T_0}=\lambda\left(\frac{3}{4}\ \overline{2g}\ /\mathrm{g}\right)^{\frac{1}{2}}x^{-\frac{1}{4}}\theta'_0 \quad (16)$$

将换热系数无量纲化,以 T^* 表示,有

$$\mathrm{T}^*=\frac{\mathrm{T}}{\lambda}\left(\frac{\mathrm{g}^2}{g}\right)^{\frac{1}{3}}=1.03\left(\frac{\mathrm{g}^2}{g}\right)^{\frac{1}{12}}x^{-\frac{1}{4}}\theta'_0 \quad (17)$$

经归纳表 2再代入式(17)可得

$$\mathrm{T}^*=0.7134\left[(g/\mathrm{g}^2)^{\frac{1}{3}}x\right]^{-\frac{1}{4}}Pr^{0.3445} \quad (18)$$

图 3示出了该式随 x 和 Pr 的变化关系,由该图可以看出,换热系数随 Pr 增大而增大。在起始点附近换热系数很大,随着向下游流动,换热系数先很快下降,然后下降速率逐渐变慢。

3　讨论和结语

文献[1]记述了 Yilmaz和 Brauer的研究,他们用数值计算分析了液膜进口流速不为零时发展段的流动特性,经与实验数据比较,得到层流边界层发展段长度表达式

$$x_{en}(g/\mathrm{g}^2)^{\frac{1}{3}}=0.1522Re^{\frac{4}{3}} \quad (19)$$

与本文的式(15)对比,可知二者除相差一个常数外,变化规律相同,都随 Re数增大而增大,但式(19)比本文结果大,这是由于该式是在液膜进口速度不为零的情况下得到的。

对恒热流竖壁降膜层流换热,文献[1]提供了 Yih 等人关于边界层充分发展后的数值结果,其无量纲换热系数为

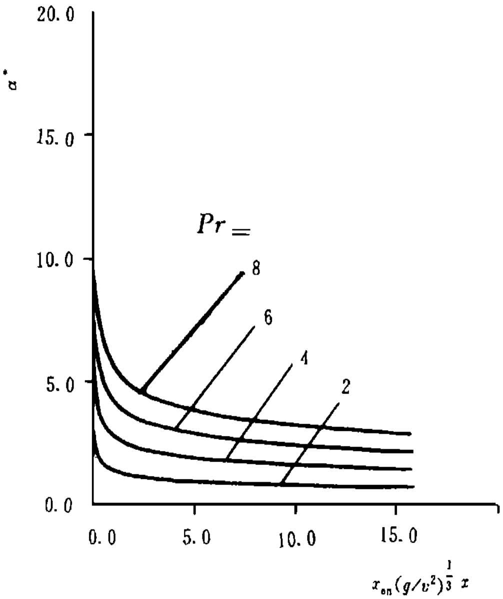

图 3　换热特性曲线

$$\mathrm{T}_{\circ}=2.262Re^{-\frac{1}{3}} \quad (20)$$

在边界层达到充分发展时,式(18)中的 x 应为温度边界层发展段长度,它与速度边界层发展段长度之比决定于 pr, pr 越大,此比值也越大,换热系数因而也就越大,当速度与温度边界层都充分发展以后,pr 对液膜内温度分布的影响就消失了,考虑到式(15)及其与温度边界层长度的关系,由式(18)有以下关系

$$\mathrm{T}_{\circ}=cRe^{-\frac{1}{3}} \quad (21)$$

式中 c 为一常数,该式说明,边界层达到充分发展以后,换热特性的变化规律与式(20)一致,其不同之处也是由于进口条件不同引起的。

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2　王启杰. 对流传热传质分析. 西安: 西安交通大学出版社, 1991

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University)// Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -178~182

Through an experimental study conducted on a circulating fluidized bed model (height 5.9 m, inner diameter 0.14 m) the formation mechanism of a wall-adhered return flow was explored and discussed with a physical model of the wall-adhered return flow proposed. The above work is meaningful for both engineering design and theoretical research of circulating fluidized beds. **Key words:** wall-adhered retun flow, circulating fluidized bed

《热能动力工程》引文分析和研究= **Analysis and Study of the Engineering Literature Citations of "Journal of Engineering for Thermal Energy & Power"** [刊,中]/Huang Mao Lin (Harbin Institute of Technology) Liu Changhe(Harbin No. 703 Research Institute)// Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -183~184

逆算法对涡轮特性柯特略尔估算的改进= **An Improvement on Kotlial Prediction of Turbine Performance by the Use of an Inverse Computation Method** [刊,中]/Xie Zhiwu, Wang Yonghong, Hong Bo, Chen Delai (Shanghai Jiaotong University)// Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -185~188

Taking Kotlial method as an example, this paper discusses the applicability of an inverse computation method for the calculation of stage superimposed type turbine performance. It has been proved that the last stage first stagnation hypothesis can be naturally fulfilled under the condition of identical design pressure ratio for each corrected stage. In case of the design pressure ratio for each corrected stage not identical given are ascertainment criteria for finding the first stagnant stage. In addition, the use of a combined sequential-inverse computation method is proposed for the treatment of critical issues, thus making a breakthrough regarding the last stage first stage hypothesis. Computation procedures have been optimized, resulting in an enhancement in evaluation precision. **Key words:** turbine, inverse computation method, Kotlial method

弯曲叶片涡轮叶栅二次流损失计算经验模型= An Empirical Model for Calculating Secondary Flow Losses of Curved Blade Turbine Cascades [刊,中]/Yu Qing (Beijing University of Aeronautics and Astronautics)// Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -189~192

On the basis of the experimental data analysis of inclined and composite curved plane cascades the author has come up with a secondary flow loss calculation model applicable for turbine cascades of curve-twist aerodynamically formed design. This model reflects the effect of such factors as blade inclination angle, aspect ratio, cascade solidity on the magnitude and distribution mechanism of secondary losses. With the help of this model evaluated in advance are the losses of a small aspect ratio gas turbine guide vane device under two forms of blades, i. e. straight and curved. The model-calculated values are in good agreement with those of the test and measuring results. **Key words:** curved blades, turbine cascade, secondary loss model

恒热流竖壁降膜发展段流动换热分析= **Flow Heat Exchange Analysis of Constant Heat Flow Vertical Wall Downcoming Liquid Film Development Section** [刊,中]/Shi Jinsheng, Shi Mingheng(Southeastern University)// Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -193~195

With the help of a boundary layer analogous solution an analysis is conducted of the laminar flow and heat exchange characteristics in the constant heat flow vertical wall downcoming liquid film development section. Obtained is the calculation expression of the development section length, liquid film thickness and non-dimensinal heat exchange factor. **Key words:** downcoming film, development section, speed boundary layer, temperature boundary layer

NG-130/39-M_2型锅炉的节能技术改造与运行= **Energy Saving-oriented Technical Modification and Operation of a Model NG-130/39-M_2 Boiler**[刊,中]/Cheng Qingang, Bao Yanjun, Zhang Guojun, et al (Harbin Power Equipment Design Institute)// Journal of Engineering for Thermal Energy & Power. -1998, 13(3). -196~199

Through the tests of a NG-130/39-M_2 boiler installed at a thermal power plant and its pulverized coal system analyzed are some causes leading to the excessively high fly ash and slag combustible content and ex-